Multifractal Approach to Study the Earthquake Precursory Signatures Using the Ground-Based Observations

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Abstract

In a series of papers by Smirnova and Hayakawa, fractal analyses of the ULF emissions in the frequency range of f = 0.001–0.3 Hz have been performed based on the geomagnetic data obtained in seismic active regions including Guam Island and Izu Peninsula. A certain dynamics of the spectrum slopes and the corresponding first-order fractal dimensions have been revealed in relation to the preparation phase of some strong earthquakes (EQs). In order to advance such a fractal approach which seems to be very promising for development of the EQ forecasting methods, we consider multifractal aspects in the analysis of geophysical data dynamics. First, as a case study, the seismicity distribution in the Kobe area of Japan is concerned in relation to the powerful Kobe EQ on 17 January 1995. Applying a multifractal approach, we have revealed that there is a gradual decrease in the certain high-order fractal dimensions which were obtained from the spectrum of singularities (multifractal spectrum) of the local seismicity distribution when the date of the Kobe EQ was approached. Many examples of the multifractal spectrum dynamics in relation to major EQs is introduced as a statistical study. It is then concluded that the multifractal analysis of geophysical data could be a promising tool for extraction of the precursory signatures of the extreme natural events including strong EQs.

Keywords

Earthquake Precursor; Ground-based Geomagnetic Observations; Multifractal Approach; Earthquake Prediction

Introduction Motivation for a Multifractal Approach

The concept of self-organized criticality (SOC), which has been first introduced by Bak et al. (1988) to explain the 1/f noise (flicker noise) and scale-invariant (fractal) structure, can be considered as a general principle governing the behavior of a certain class of complex dissipative dynamic systems toward a rupture. This SOC theory widely used to investigate the dynamics of natural hazard systems including earthquakes (EQs) (e.g., Goltz, 1997) has been utilized in this paper as one of the principal points in our complex approach to study the EQ preparation processes.

A lot of evidence has been accumulated on the important role of electromagnetic precursors of EQs for the purpose of short-term EQ prediction (e.g., recent books by Hayakawa and Molchanov (2002), Molchanov and Hayakawa (2008), Hayakawa (2009, 2012)). Since the first attempt of fractal analysis for the seismogenic ULF emissions (Hayakawa et al., 1999), a phenomenological model of the large-scale evolutionary processes between two violent EQs based on the SOC concept has been suggested. Four principal stages in the EQ preparation processes have been taken into consideration: initial phase (random chaos just after the first EQ when the tectonic energy is fully released), subcritical, critical and super-critical stages. Supercritical stage is the final stage of the SOC evolution, where there is a high probability of the next violent EQ. Subcritical and critical stages are intermediate stages of the SOC evolution. Since the principal feature of the SOC dynamics is a power-law distribution (or fractal organization) of the system parameters both in space (scale-invariant structure) and time (temporal-invariant structure), fractal methods can be used to investigate nonlinear scaling characteristics of such a distribution at different stages of the strong EQ preparation. In our previous studies (Smirnova, 1999; Gotoh et al., 2003, 2004; Smirnova et al., 1999, 2001, 2004, 2010; Ida et al., 2005, 2006; Ida and Hayakawa, 2006; Smirnova and Hayakawa, 2007; Hayakawa and Ida, 2008), the focus was on ULF (f=0.001-1Hz) geomagnetic measurements in seismo-active regions, since those ULF waves are the most sensitive to the variation of geoelectric parameters of

Earth's crust at typical depth of EQs (see e.g., Hayakawa et al., 2007; Hayakawa, 2012). Then, it is concluded that precursory signatures of the strong EQs are manifested in dynamics of the scaling characteristics (spectrum slopes and fractal dimensions) of the ULF emissions registered in seismic active regions. Here the multifractal approach was introduced to extract the EQ precursory signatures from spatial and temporal variations of geophysical data. The primary question which arises, is "Why multifractal approach should be used?" The answer relates mainly to the clustering of seismicity and an analogy between the destruction processes and the process of a multifractal measure generation. In this paper, we do not deal with seismogenic ULF emissions, but with the simple EQ distribution. First of all, the seismicity forms spot-like structures in a wide range of scales as seen in Fig. 1 taken from Kiyashchenko et al. (2004). Such structures are similar to multifractal measure distribution. Second, the destruction process leads to the formation of multifractal-like structures. The simple mechanical analogy is illustrated in Fig. 2(a). When there appears a crack, the initial stress M is redistributed around its tips (Step 1). In the zone B, the stress level decreases. Let us assume that its average value is M_1. In the zone A, the stress increases to the value $M_2 > M_1$. On the second step, if the other cracks appear in the zones A and B, the stress field is redistributed in a similar proportion $M_2 : M_1$ (see Step 2 in Fig. 2(a)). This process is very similar to the multiplicative process of multifractal measure generation (see the corresponding figures in Feder (1988) and Mandelbrot (1989)).

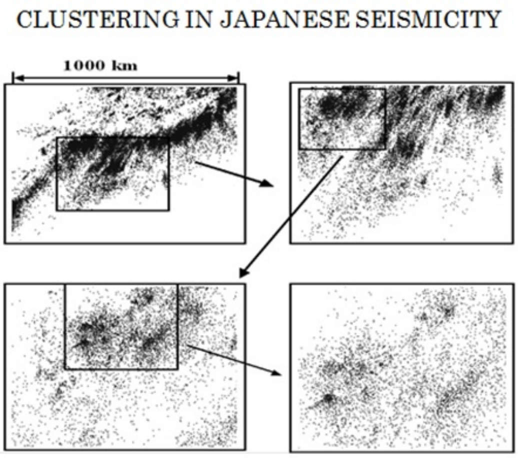

FIG. 1 AN EXAMPLE OF SEISMICITY CLUSTERING ON DIFFERENT SPATIAL SCALES (SEE KIYASHCHENKO ET AL. (2004) FOR DETAILS).

Multifractal Formalism

Multifractal approach is a synthesis of the fractal analysis, which is more general than the monofractal approach and can be presented by a spectrum of generalized fractal dimensions d(q) and spectrum of singularities $f(\alpha)$ (multifractal spectrum) (e.g., Goltz (1997), Badii and Roliti (1997), Hayakawa and Ida (2008)). The physical and mathematical meanings of these parameters will be given later. An example of such spectra for a binomial multiplicative process presented in Fig. 2(b) is shown in Fig. 3. Curves 1 correspond to the case M_1=0.6 and M_2=0.4, while Curves 2 correspond to M_1=0.8 and M_2=0.2 (see Kiyashchenko et al. (2003) for details). It is seen from Fig. 3 that the range of generalized fractal dimensions d(q) is wider for the more contrast redistribution of the mass M_1, M_2 (more inhomogeneous media). The same feature can also be noted on the basis of the multifractal spectral behaviour (see $f(\alpha)$ curves in the right part of Fig. 3). The $f(\alpha)$ curve is known to extend with an increase in contrast of M_1 and M_2. A general case of the real multifractal spectrum is presented in Fig. 4. A lot of parameters taken from the $f(\alpha)$ curve can be informative: the Lipshitz-Holder exponents α_0, α_1, α_{min}, α_{max}, the range $\Delta\alpha=\alpha_{max}-\alpha_{min}$, the dimensions D_0, $d(1) = \alpha_1$, etc. Therefore, by tracing $f(\alpha)$ changes as well as the changes in spectrum of the generalized fractal dimensions d(q), it is possible for us to study the dynamics of natural tectonic systems and to investigate EQ preparation processes.

Multifractal Properties of EQs: World-wide Studies

Up to now, many workers have studied fractal and chaotic features of EQs. So the hierarchical properties of seismicity have been firstly described in the early works of Sadovskiy (e.g. Sadovskiy et al., 1984). The more complete studies in this field are summarized in the Lecture Note by Goltz (see Goltz, 1997 and references therein). According to the paper by Haikun (1993) quoted in Goltz (1997) some precursory changes of the multifractal $f(\alpha)$ curve have been observed inrelation to the strong EQs occurring in the Datong area, China during the 1970-1991. The schematic illustration of such precursory behaviour is shown in Fig. 5. The following peculiarities observed before major EQs can be noted based on this illustration.

- The multifractal spectrum is found to extend (corresponding $\Delta\alpha$ increases). The increase in $\Delta\alpha$ means a transition from homogeneous (random, space filling) to heterogeneous (ordered, complex, clustered) patterns.
- α_{min} and α_{max} shift to the right and α_0 increases. The shift to the right of α_{min} means that the

clustering within the most clustered areas becomes more intense (the local fractal dimension increases within these vicinities). The analogous shift of α_{max} indicates that the clustering within the sparse areas becomes also enhanced. Thus an overall increase in the degree of clustering can be expected.

- The increase of α_0 shows that most clusters now possess a higher local fractal dimension than before. An increase of $f(\alpha_0)$ means a rise of D_0-capacity dimension which is not usually observed.
- The increase in $\Delta f(\alpha)$ indicates that a change has occurred in the ratio of highly clustered and sparsely populated areas.

There is another paper by Hirabayashi et al. (1992), in which the dynamics of d(q) is presented in Fig. 6 for the California (left part) and Japan (right part) EQs. For each (a) or (b), the left panel in the bottom refers to the seismic quiet condition and the right, the seismic active condition.

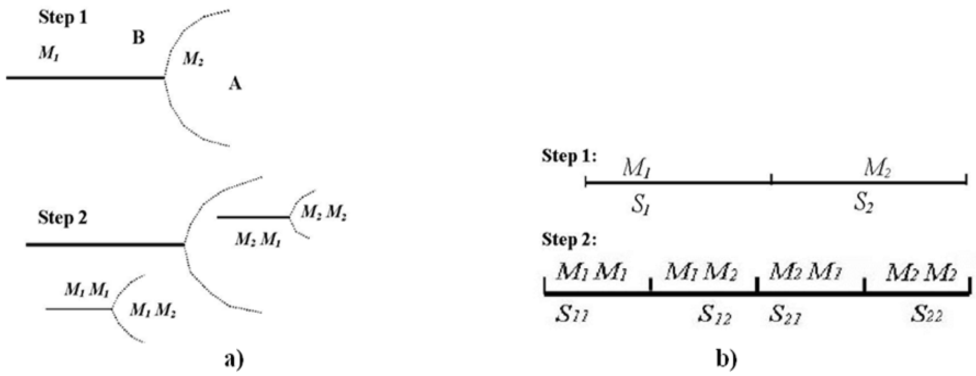

FIG. 2 THE QUALITATIVE ANALOGY BETWEEN THE DESTRUCTION PROCESSES (a) AND THE PROCESS OF A MULTIFRACTAL MEASURE GENERATION (b)

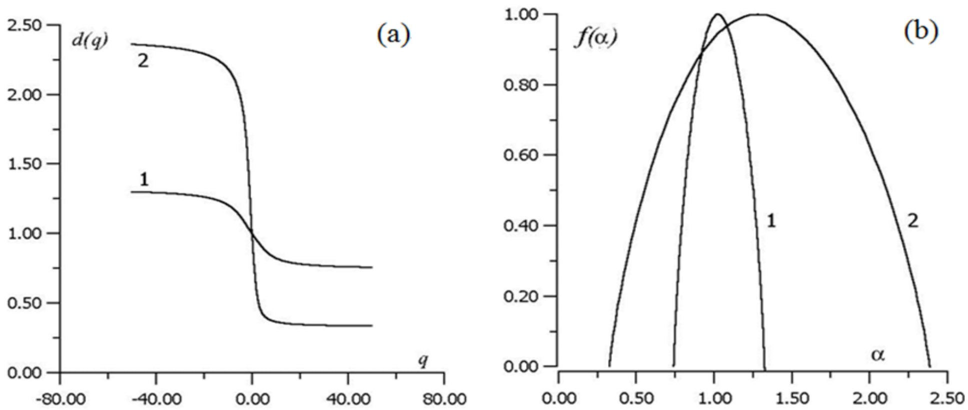

FIG. 3 SPECTRUM OF THE GENERALIZED FRACTAL DIMENSIONS (a) AND SPECTRUM OF SINGULARITIES (MULTIFRACTAL SPECTRUM) (b) FOR A BINOMIAL MULTIPLICATIVE PROCESS PRESENTED IN FIG. 2(b). (CURVE 1: M_1=0.6, M_2=0.4; CURVE 2: M_1=0.8, M_2=0.2).

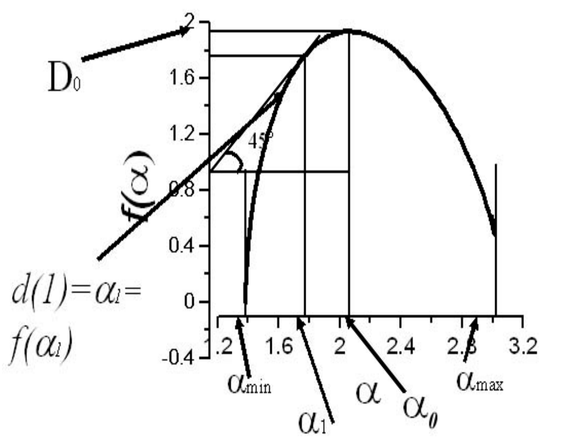

FIG. 4 MULTIFRACTAL SPECTRUM (THE GENERAL CASE)

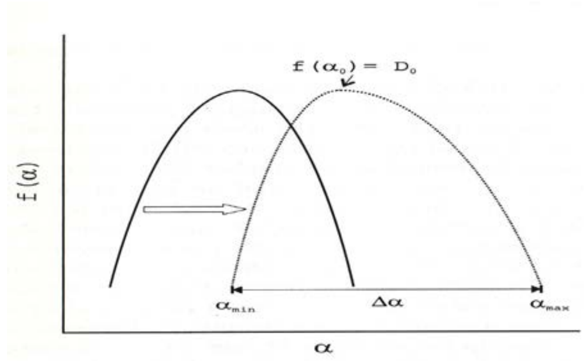

FIG. 5 PRECURSORY BEHAVIOUR OF MULTIFRACTAL SPECTRA AS OBSERVED BY HAIKUN (1993). THE *f(α) – α* CURVE CHANGES FROM THE SOLID ONE TO THE DASHED ONE SEVERAL YEARS BEFORE A MAJOR EQ OCCURS

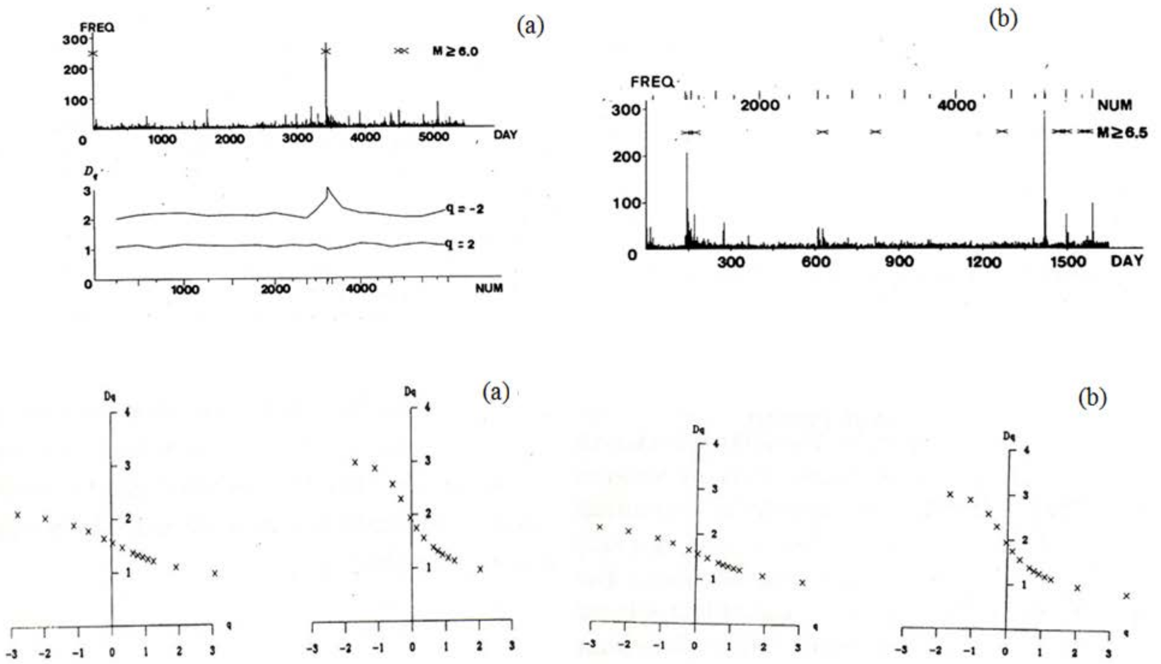

FIG. 6 CHANGES OF THE GENERALIZED FRACTAL DIMENSIONS d(q) FOR CALIFORNIA (a) AND JAPAN (b) EQS. FOR EACH (a) OR (b), THE LEFT PANEL IN THE BOTTOM REFERS TO THE SEISMIC QUIET CONDITION, WHILE THE RIGHT, SEISMIC ACTIVE CONDITION (HIRABAYASHI ET AL.,1992).

Our Studies of Multiracial EQ Precursors

The world-wide studies of the multifractal properties of seismicity distribution seem to be not so rigorous and complete, and their results are often inconsistent with each other. So we have carried out our own researches to understand if there are any pronounced precursory signatures in dynamics of the seismicity multiracial characteristics.

Data Used for Multiracial Analysis of the Seismicity

Two EQ hypocenter catalogs have been utilized for our multifractal analysis: (1) Japan University Network EQ Catalog Hypocenters, published by Earthquake Research Institute, University of Tokyo (http://www.eri.u-tokyo.ac.jp). This catalog contains the EQs with magnitude M > 2.0 occurring in the area with geographical coordinates φ = 26– 48° N and λ = 128 − 148°E during the temporal period from 1985 to 1996. (2) Southern California EQ hypocenter catalog containing the EQs with magnitude M > 1.0 occurred in the area with geographical coordinates φ = 1 − 60°N and λ = 26 − 178°W during the temporal period from 1982 to 1999 (http://www.scecdc.scec.org/catalog).

Our consideration was restricted only to those events, which occurred at the depth less than 60 km, and the strong EQs were selected with magnitude M > 6.5 from both catalogs to study the dynamics of regional seismicity distribution prior to those strong events. For each of the strong EQs considered, the sub-catalog of the seismicity registered in its surrounding area was selected for analysis. The surrounding area is taken in the form of a box with the side A (Fig. 7) centered at the EQ epicenter. The size A of the area has to be selected according to the size of the rupture area of the strong EQ. Also this area should contain sufficient amount of data for multifractal analysis of the seismicity in a sliding temporal window. The available size A of the surrounding area has been roughly estimated. The size L of the rupture area can be estimated using the empirical relation (Sobolev and Ponomarev, 1999; Sobolev, 1990): lgL = 0.6M − 2.5, where M is the EQ magnitude. Computational results of the L values are shown in Table 1.

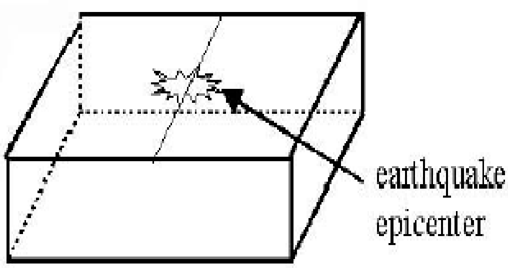

FIG. 7 BOX - LIKE AREA NEAR AN EQ EPICENTER.

The effective radius of the surrounding area (equal to A/2), which has to be selected for analysis, must not exceed several lengths of the rupture of an expected strong EQ.

TABLE 2 THE PARAMETERS OF THE STRONG EQS SELECTED FOR ANALYSIS.

N	data	φ	λ	z, km	M	S, km^2
1	27/10/88	36.3° N	141.749° E	40	7.7	400 × 400
2	02/11/89	39.736° N	143.39° E	0	6.6	400 × 400
3	07/02/93	37.658° N	137.309° E	26.5	6.6	400 × 400
4	04/10/94	43.383° N	147.928° E	46.2	8.1	400 × 400
5	28/12/94	40.434° N	143.867° E	14.1	7.5	400 × 400
6	07/01/95	40.232° N	142.425° E	55.9	7.2	400 × 400
7	17/01/95	34.583° N	135.027° E	33.4	7.2	400 × 400
8	17/02/96	37.306° N	142.643° E	59.1	6.7	400 × 400
9	19/10/96	31.798° N	131.972° E	44.6	6.6	400 × 400
10	24/11/87	33.01° N	115.85° W	11.2	6.6	200 × 200
11	28/06/92	34.2° N	116.44° W	1	7.3	200 × 200
12	16/10/99	34.594° N	116.271° W	0	7.1	200 × 200

TABLE 1 THE RUPTURE SIZE L OF AN EQ WITH MAGNITUDE M

M	4.0	4.5	5.0	5.5	6.0	6.5	7.0	7.5	8.0
L, km	0.8	1.6	3.16	6.3	12.3	25.1	50.1	100	200

That is an important condition for searching the precursory phenomena using the methods suggested in this paper. In fact, if the size of the rupture area of the selected strong EQ is much smaller than that of surrounding area (for example, if the size of surrounding area is A = 400 km and the size of rupture area is L = 6.3 km for the EQ with M = 5.5), the main part of the seismicity located in this area has no influence on the process of preparation of that strong EQ. Since we have selected the EQs with M>6.5, the corresponding rupture area is L>25 km (see Table 1). In such a case, the size of the surrounding area A= 200–400 km seems to be suitable for multifractal analysis: on the one hand, it is in appropriate relation with the rupture size; on the other hand, such area contains sufficient amount of data for the analysis of multifractal characteristics of seismicity distribution in sliding temporal windows of reasonable length. Taking into account the amount of data in the sub-catalogs used for analysis and the chosen temporal window (less than approximately 3 years in our case), the size of surrounding area 400 × 400 km^2 seems to be acceptable for Japanese EQs, and the size 200 × 200 km^2 is suitable for the EQs of Southern California. We can take the smaller size of surrounding area for the EQs of Southern California since the Californian catalogs contain a larger amount of data. Overall, 12 strong EQs with M > 6.5 have been selected from both catalogs. The information concerning these EQs is summarized in Table 2. The corresponding sub-catalogs of seismicity have been analyzed in the EQ surrounding areas of the size S km^2. Here N is the serial number of EQ, φ, latitude of the epicenter, λ, its longitude, z, the depth of the hypocenter, and S is the square of surrounding area centred on the epicenter of the EQ.

Analysis Procedure

For each of the sub-catalogs, the following multifractal characteristics have been calculated as seen in Fig. 4: $S = d(1)$ (information dimension), $d(2)$ (correlation dimension), α_{min}, $= d(+\infty)$, and α_{0x} (the abscess of the top of the multifractal spectrum).

Calculations have been fulfilled with a sliding temporal window, whose length was selected individually in each case to contain an adequate set of statistics (about 1000 events). In our case, 2D (two dimensional) distribution of the seismicity hypocenters has been studied as seen in Fig. 8. The distribution function $p_j(\Delta)$ is defined as:

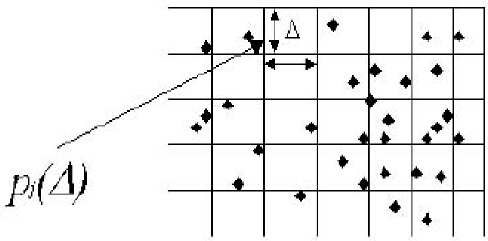

FIG. 8 EQ EPICENTERS CONTINUUM.

$$p_j(\Delta) = \frac{N_j}{N} \tag{1}$$

where N_j is the number of EQs occurring in the cell with number j and size Δ, and N is the total number of

EQs in the considered region. The generalized fractal dimension *d(q)* of the order *q* can be determined from the Renyi entropy (Kiyashchenko et al., 2003).

Let us introduce the Renyi entropy of order q:

$$\ln\ (I_q(\Delta)) = \frac{\ln\ (\Sigma_j p_j^q(\Delta))}{1-q},\ \text{if}\ q \neq 1 \quad (2)$$

$$\ln\ (I_q(\Delta)) = -\sum_i p_i(\Delta)\ln(p_i(\Delta)),\ \text{if}\ q=1. \quad (3)$$

Then, the generalized fractal dimension of the order q is defined as:

$$d(q) = \lim_{\Delta\to 0}\frac{\ln(I_q(\Delta))}{\ln(1/\Delta)} \quad (4)$$

So the generalized fractal dimension *d(q)* can be determined as a slope of the best fit line representing the Renyi entropy *I(q)* versus 1/Δ in the log-log plot. It is possible to show that the Holder exponent α and the $f\ (\alpha)$ curve can be retrieved from the spectrum of generalized fractal dimensions *d(q)* using the transforms:

$$\alpha(q) = \frac{d}{dq}((q-1)d(q));$$
$$f(\alpha(q)) = q - d(q)(q-1) \quad (5)$$

Dynamics of four multifractal characteristics, namely, the minimal value of the Hölder exponent α_{min} = d(+∞), the information dimension $S = \alpha_1 = d(1)$, the correlation dimension *d*(2), and the abscissa of the top of multifractal spectrum α_{0x} have been studied prior to strong EQs listed in Table 2. These multifractal characteristics provide us with the important information on the inhomogeneity of seismicity distribution and the level of seismicity clustering in a wide range of scales. So, the entropy S can be treated as the measure of inhomogeneity of the distribution of the seismicity: the lower (higher) values of S correspond to more (less) inhomogeneous distributions (see Kiyashchenko et al., 2003). The correlation dimension *d*(2) characterizes the degree of seismicity clustering. Lower values of *d*(2) indicate stronger clustering in a wide range of scales. The value of α_{min} characterizes the degree of seismicity clustering in seismically active parts of the considered region in some range of scales. The smaller values of α_{min} can be interpreted as a manifestation of stronger clustering in densely populated areas. The value of α_0 is sensitive to the heterogeneity of the seismicity distribution in sparsely populated areas. The higher value of α_0 corresponds to more heterogeneous cases (see Kiyashchenko et al., 2003).

Results

The results of calculation of multifractal characteristics for each particular EQ listed in Table 2 can be found in the paper by Kiyashchenko et al. (2003). Generally, the tendency of a decrease in the multifractal characteristics α_{min}, *S* and *d(2)* and an increase in α_0 have been revealed before the mainshocks. As a case study, the case of well-known Hyogo–ken Nanbu (Kobe) EQ of 17 January, 1995 in Japan (φ = 34.583°N, λ = 135.02°E, *M* = 7:2, depth =33 km) is presented in Fig. 9. The length of sliding temporal window is taken equal to 0.5 × 10^8 s. It is seen that the decrease of the multifractal characteristics α_{min}, *S* and *d(2)* and the increase of α_0 started approximately two years before the EQ. After the EQ, the multifractal characteristics tend to recover to their initial level. Such post-EQ behavior can be considered just as a recovery process, when the EQ focal system breaks down to the more disordered (chaotic) state after the release of main portion of seismic energy.

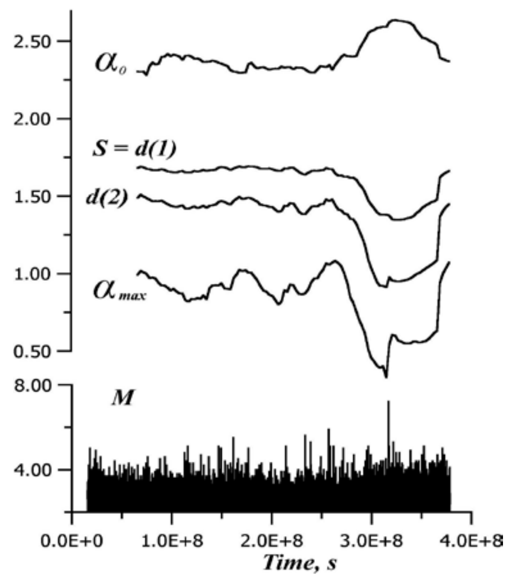

FIG. 9 DYNAMICS OF THE HIGHER-ORDER GENERALIZED FRACTAL DIMENSION (α_{min},), ENTROPY (*S*), CORRELATION DIMENSION d(2) AND ABSCISSA OF THE TOP OF MULTIFRACTAL SPECTRUM α_0 FOR A PARTICULAR CASE OF THE M=7.2 KOBE EQ WHICH OCCURRED IN JAPAN ON JANUARY 17, 1995.

In order to highlight the general tendencies in the variations of multifractal characteristics prior to individual strong EQs, the superposed epoch method is applied to all the cases considered in Table 2. The procedure of the superposed epoch analysis is explained as follows. First, all the plots representing the variation of certain characteristics are shifted along the temporal axis, so that the moment *t* = 0 corresponds to the main event occurrence time. Then,

the certain values of multifractal characteristics corresponding to a particular moment are stacked over all plots related to different EQs and averaged. The dynamics of the values α_0, d(1)=S, d(2), α_{min}, obtained by this method is shown in Fig. 10.

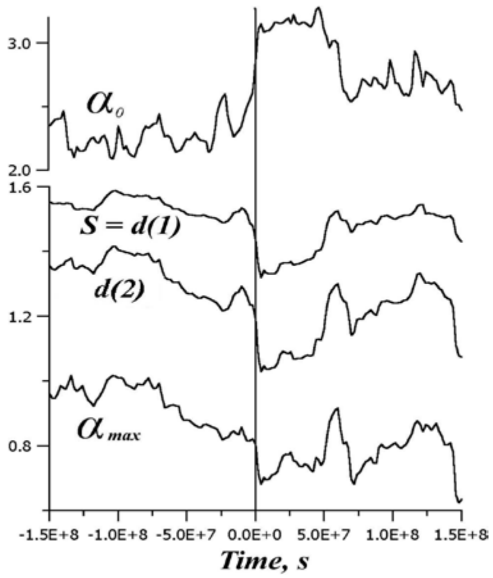

FIG. 10 DYNAMICS OF THE SAME MULTIFRACTAL CHARACTERISTICS AS PRESENTED IN FIG. 9 FOR THE KOBE EQ, BUT FOR THE SUPERPOSED EPOCH SUMMARY OBTAINED FROM 12 EQS IN TABLE 2.

For the superposed epoch analysis, the length of sliding temporal window for the calculation of multifractal characteristics is taken equal to 0.5×10^8 s for Japanese EQs and equal to 0.15×10^8 s for Californian EQs. The individual patterns of some EQs are neglected in this case, since the length of the temporal windows is not selected individually for each EQ. But even under such a condition, the general tendencies can be clearly seen in Fig. 10. So the multifractal characteristics α_{min}, *S* and *d(2)*, tend to decrease and α_0 tends to increase before the strong EQs. It can be treated as a signature of an increase in spatial inhomogeneity of the seismicity distribution in a wide range of scale levels, preceding strong EQs. Thus, it is found that the seismicity distribution evolves from the more homogeneous (disordered) state towards the more clustered (ordered) state. To compare the results for real and simulated seismicity, we have calculated the correlation dimension *d(2)*, information dimension *d(1)*, and the abscissa of the top of multifractal spectrum α_0 in a sliding temporal window of 20000 s for the synthetic seismicity catalog, obtained as the result of simulation of the destruction process (see Kiyashchenko et al. (2004) for details). The results are shown in Fig. 11. The calculations of the high-order generalized fractal dimension α_{min}, have not been performed because of too small number of events.

It is clearly seen that the correlation and information dimensions tend to decrease before the main rupture moment. The multifractal characteristics α_0 increase before the main rupture. These results support the conclusion concerning the increase of heterogeneity of the seismicity distribution in a wide range of scales prior to main rupture. So the tendencies which have been revealed in the behavior of real seismicity are in agreement with the results of simulation of the destruction of elastic body with a number of shear cracks reported in Kiyashchenko et al. (2004). Therefore, it can be argued that multifractal analysis of the seismicity distribution dynamics is one of possible sources of information on the precursory evolution of the Earth's crust.

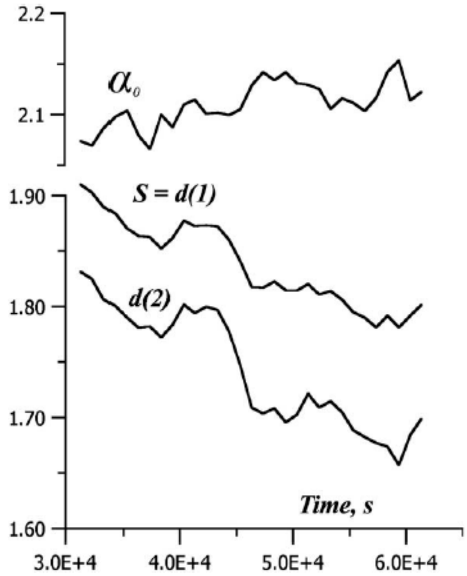

FIG. 11 DYNAMICS OF MULTIFRACTAL CHARACTERISTICS OF THE SYNTHETIC SEISMICITY DISTRIBUTION OBTAINED AS A RESULT OF SIMULATION OF DESTRUCTION PROCESS.

Discussion and conclusions

We have analyzed the world-wide studies of multifractal properties of seismicity and highlighted certain tendencies in dynamics of the seismicity multifractal spectra prior to main strong EQs. As it follows from the corresponding researches (Goltz, 1997), the seismicity multifractal spectrum extends in such a way that α_{min} and α_{max}, shift to the right and α_0 increases prior to strong EQs. Those peculiarities mean the transition from homogeneous (random) to heterogeneous (ordered, clustered) patterns; intensification of the clustering within rupture areas; increment of the local fractal dimension; and a change in the ratio of highly clustered and sparsely populated areas. However, those results have been obtained on the basis of poor statistics. So we have fulfilled an

additional multifractal analysis of the seismicity distributions before 12 strong EQs occurring in Japan and Southern California during an extended period of more than 10 years (see Table 2). We have tried to receive sufficient statistics to draw a definite conclusion about seismicity multifractal dynamics, and have calculated four multifractal characteristics of seismicity, namely, the minimal value of the Hölder exponent $\alpha_{min} = d(+\infty)$, the information dimension $S = \alpha_1 = d(1)$, the correlation dimension $d(2)$, and the abscissa of the top of multifractal spectrum α_0, for seismicity distribution around 12 strong EQs listed in Table 2. Then their dynamics in the process of approach of the main EQ has been studied. A clear tendency of decrement of the multifractal characteristics α_{min}, S and $d(2)$, and increment of α_0 before the main shocks have been revealed. It can be interpreted as a signature of increase of spatial inhomogeneity of the seismicity distribution in a wide range of scale levels, preceding strong EQs. Thus, seismicity distribution evolves from the more homogeneous (disordered) state towards the more clustered (ordered) state. That is consistent with the few world-wide studies. Also the revealed dynamics is consistent with the dynamics of multifractal characteristics of the synthetic seismicity distribution obtained as a result of the destruction process simulation (Kiyashchenko et al., 2004). In view of our reliable statistics, it is possible to argue that the variations of multifractal characteristics presented here appear real due to the processes of the reorganization of the seismicity but not due to numerical errors or instability of the procedure of calculation of generalized fractal dimensions. So, the results obtained offer an opportunity to use multifractal scaling characteristics of the seismicity for monitoring of the destruction process in seismically active areas and thus for a forecast of strong seismic events. Appreciable information on pre-rupture evolution of fault (crack) network in the lithosphere could be provided by the study of such multifractal dynamics.

On the basis of the research fulfilled in this paper, it can be concluded that multifractal analysis of geophysical data could be a promising tool for extraction of the precursory signatures of the extreme natural events including destructive EQs. However, the anomalous variations in multifractal parameters of seismicity distribution is found to begin a few years before the main shock, which seems to be consistent with the former corresponding results by Haikun et al. (1993) and Hirabayashi et al. (1992). Thus, this kind of EQ precursor based on the seismicity distribution is likely to be a typical medium-term EQ prediction. When any particular region with expectation of a big EQ has been known from the seismological point of view, the method proposed in this paper would be of extreme importance in predicting EQ. In order to realize the real EQ prediction, it is highly required to have additionally the corresponding analysis for electromagnetic effects (Molchanov and Hayakawa, 2008; Hayakawa and Ida, 2008)), because these electromagnetic effects are considered to be promising candidates of short-term precursors.

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